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Probability of Fire-Stopping Precipitation Events

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Abstract—Fire managers in the Northwestern United States are often confronted by the problem of determining when precipitation might stop an ongoing fire. The possibility that a useful probability for fire-stopping precipitation could be developed from historical weather records was investigated. Persons familiar with weather and fire behavior suggested a fire-stopping precipitation criterion of "at least 0.5 inches of precipitation in 5 days or less." Daily precipitation data from four fire weather stations for the period 1970 to 1985 were used to estimate the chance that the criterion would be satisfied by a specified date in the fire season. The Weibull probability distribution was found to be an excellent fit for the problem. The method of fitting the distribution to the data is described and results given for four weather stations in the Northern Rocky Mountains. This method can be applied to other "fire-stopping" criteria using the same technique.

Keywords: fire season, probability, fire control, forest fires, prescribed natural fires, fire weather, Northern Rocky Mountains

During the early summer of 1988, when lightning began to ignite forest fires in our western parks and wilderness areas, fire managers tried to estimate how large such fires might become if they were not suppressed. Various scenarios such as worst-case, serious, or normal weather conditions were considered (Rothermel 1991; Stiger and Bushey 1991). A lack of precipitation during the previous fall and winter combined with uneven amounts of spring precipitation resulted in the onset of serious drought and severe fires in our Western States.

Drought sets the stage for severe fire by conditioning the vegetation so it ignites easily and fire spreads rapidly when dry lightning strikes and cold fronts with strong winds pass through. These possibilities are well known to fire managers and must be included in long-range fire predictions. In a worst-case scenario, drought can be assumed to continue through the summer and into the fall. The drought can be included in estimates of fire growth projected through this period. The projections for ultimate fire size become larger for each sequential fire projection as the drought continues, but as Rothermel (1991) points out, this would not be very helpful to fire managers without some basis for projecting the conditions that could stop the fire. The problem is aggravated late in the season when winds generally blow the strongest and fires grow the fastest.

The clarity of hindsight in October is not available in June when forecasts must be made. To help solve this dilemma, we developed a method to determine the probability of fire-stopping precipitation from climatological records. With this information, fire projections based on continued drought can be accompanied by the probability of precipitation sufficient to extinguish or subdue the fires so fire control is effective.

The use of climatological data to indicate the probability a fire will end should be much more reliable than the use of such data to predict the growth of fires. Wind, humidity, fuel moisture, fuel continuity, slope, and ignition must be in proper balance for fires to grow. Estimates of these conditions as well as fire situation must be available to predict fire growth. However, a significant rainfall or snowstorm, or several days of light rain and high humidities, can stop a fire's spread or slow it enough so fire control is effective. There is no guarantee that precipitation will occur by a specific date; the data should be presented as a probability the fire manager can use to estimate risk.

This paper captures an idea and analysis method. It is not intended as a how-to-do-it paper, nor as a training manual. As with many research products, additional work is needed to develop procedures for its use and application.

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ANALYSIS

Fire data were searched to estimate the amount of precipitation needed to slow or stop a spreading fire. This effort proved fruitless; instead, we used the opinions of persons familiar with fire and fire weather to define the precipitation event. For the area of the Northern Rocky Mountains represented by the four stations we studied, the defined precipitation event was: << at least 0.5 inches of precipitation accumulated in 5 days or less >>. This definition could be altered to better represent this area or other areas of the country. This is not, however, the object of our probability analysis. Our object is to determine, *given a starting date what is the probability of a fire-stopping precipitation event occurring by any succeeding date*?

Climatological data for four arbitrarily chosen weather stations were retrieved from the National Fire Weather Data Library. Daily precipitation was used to estimate the chance for a defined precipitation event to occur by a specified date in the typical fire season. The Weibull distribution was used to estimate probabilities. This distribution is commonly used in weather statistical modeling. Data needed from the weather files are the Julian day and the amount of precipitation for the appropriate time of year. For this analysis in the Northern Rocky Mountains, we used data from July 1 to October 15, the period that includes the height and the end of the fire season. Data were available from 1970 to 1985. A FORTRAN routine counted the number of days between July 1 and the defined precipitation event for each year. The data were compared with the weather file to locate gaps arising from missing days; data with gaps were deleted.

The next step was to rank << days until a precipitation event >> by year, with the shortest interval having rank 1 and the longest interval the highest rank. We created a file containing the rank as well as the number of days until a precipitation event. After mathematically transforming these two values, the data were fit to a least-squares line. The parameters of the Weibull distribution were determined from the least squares coefficients as follows:

Let the ranks be 1, 2, ..., n and the corresponding days until a precipitation event be $d(1), \ldots, d(n)$. Then

$$Y(i) = \ln[\ln(1/(1-F(i)))] \tag{1}$$

where

$$F(i) = (i - 0.5)/n. \tag{2}$$

If

$$X(i) = \ln(d(i)), \tag{3}$$

then the line obtained from a least squares fit to $X(i)$, $Y(i)$ is:

$$Y = a + bX \tag{4}$$

The parameters of the Weibull distribution are calculated from the least squares coefficients, a and b. The probability density function, $f(\cdot)$, for the Weibull distribution is:

$$f(w; \eta, \sigma) = (\eta/\sigma)(\tfrac{w}{\sigma})^{\eta-1} \exp\left[-(\tfrac{w}{\sigma})^{\eta}\right] \tag{5}$$

where $w \geq 0$ is the elapsed (waiting) time and $\eta > 0$, $\sigma > 0$ are parameters of the distribution. The parameter $\eta = b$, the slope of the least squares line above, and the parameter $\sigma = \exp(-a/b)$.

The cumulative distribution, $F(\cdot)$, is then found from:

$$F(W; \eta, \sigma) = 1 - \exp\left[-(\tfrac{w}{\sigma})^{\eta}\right] \tag{6}$$

We found that the fit could be significantly improved by selecting a starting day for the distribution. The best starting day was chosen by shifting a trial starting date from July 1 to July 26 in 5-day increments for each station. We picked the optimum shift to be the least squares fit (4) with the minimum root mean square error and used those coefficients to determine the best Weibull distribution for that station.

RESULTS

The Weibull parameters for the four chosen weather stations as well as the starting days are given in table 1. In addition, the "best" fits are shown in figures 1 to 4 and tabulated in tables 2 to 5. The figures depict the cumulative distribution from equation (6) and the probability distribution function from equation (5).

GENERATING THE STATISTICS FOR A STATION

To apply the Weibull probability technique to precipitation data at any station, proceed as follows:

1. Obtain yearly precipitation records from the desired weather station.
2. For each year, determine the number of days after the cessation of spring rains to the event << at least 0.5 inches of precipitation in a 5-day period or less >>.
3. Order the time periods from (2) above from the shortest to the longest number of days.
4. Form the variables X and Y from the list obtained in step (3). Do a least squares linear fit on these variables. Write down the starting date, a, b, and the statistic r^2 for this step.
5. Shift the time forward 5 days by subtracting 5 from each $d(i)$. Throw out any negative values, rerank, and do (3) and (4) again. Do steps (3), (4), and (5) until late July.
6. Now look at the least squares fits from step (5). Pick the starting date for the best fit (largest r^2) and use those values of a and b to form the Weibull parameters for the chosen station.

Table 1—Weibull parameters estimated from least squares fit

Location	Period	Shift[1]	Start date	η[2]	σ[3]	*N*[4]
Lolo NF	1970-1985	20	July 21	1.86709	49.88164	43
Bitterroot NF	1970-1985	15	July 16	1.87097	51.09142	51
Lewis and Clark NF	1970-1985	10	July 11	1.62625	46.96404	71
Mt. Hood NF	1972-1985	20	July 21	3.14259	61.27729	72

[1] The number of days the starting date was shifted from July 1 for the best least squares fit.
[2] A parameter equal to the slope of the least squares lines.
[3] A parameter equal to exp(−*a*/*b*), where *a* and *b* are the least squares coefficients.
[4] *N* is the number of cases used to estimate η and σ.

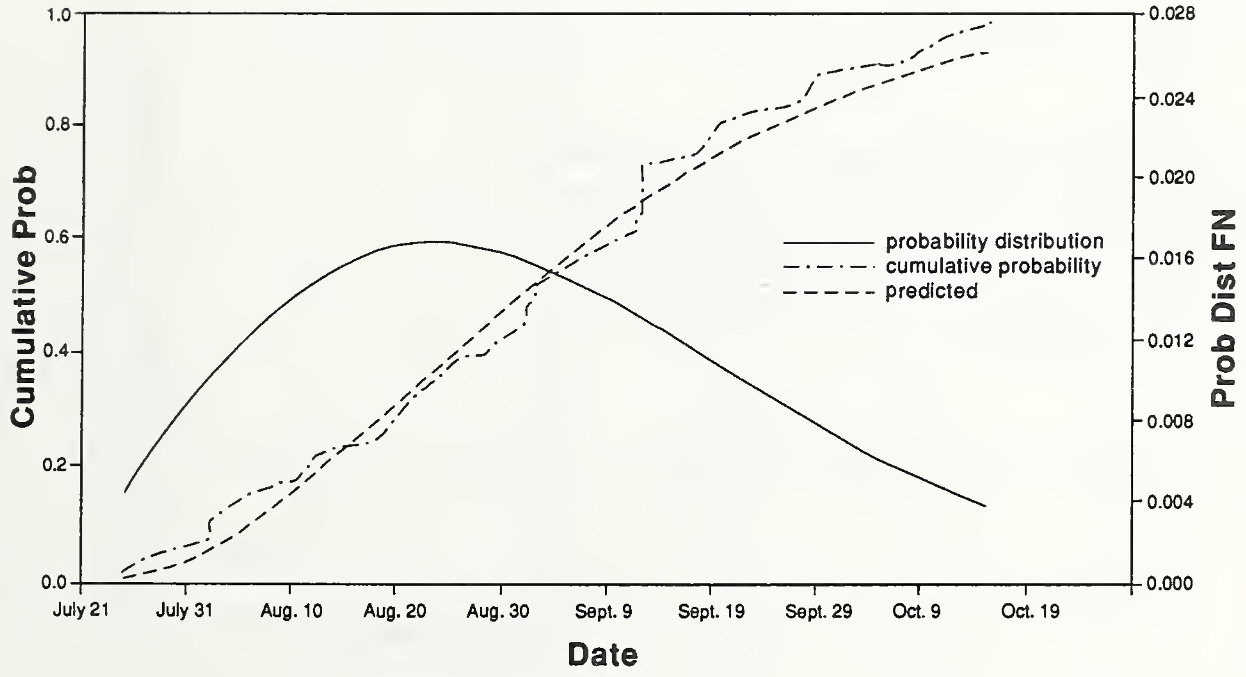

Figure 1—Cumulative probability and probability distribution for the first occurrence of a precipitation event producing 0.5 inches of precipitation in 5 days or less (data collected from 1970 to 1985 at the Ninemile weather station on the Lolo National Forest in west-central Montana). The starting date was shifted 20 days from July 1 for the best least squares fit.

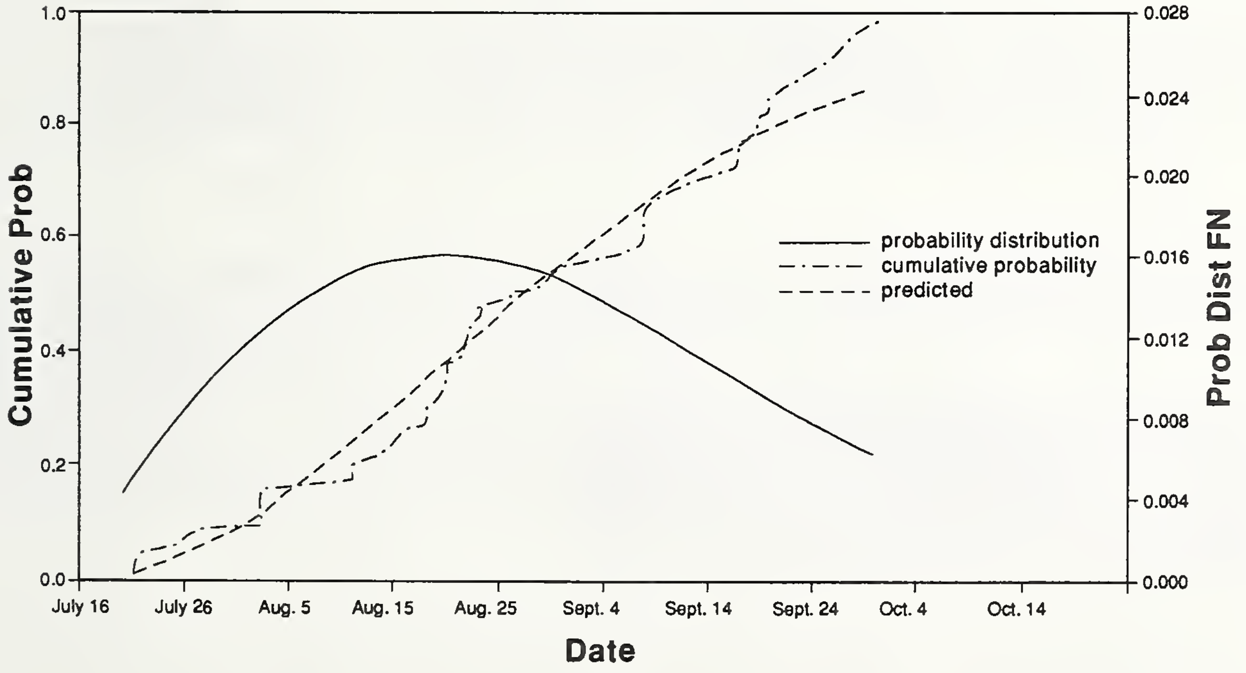

Figure 2—Cumulative probability and probability distribution for the first occurrence of a precipitation event producing 0.5 inches of precipitation in 5 days or less (data collected from 1970 to 1985 at the Westfork weather station on the Bitterroot National Forest in southwestern Montana). The starting date was shifted 15 days from July 1 for the best least squares fit.

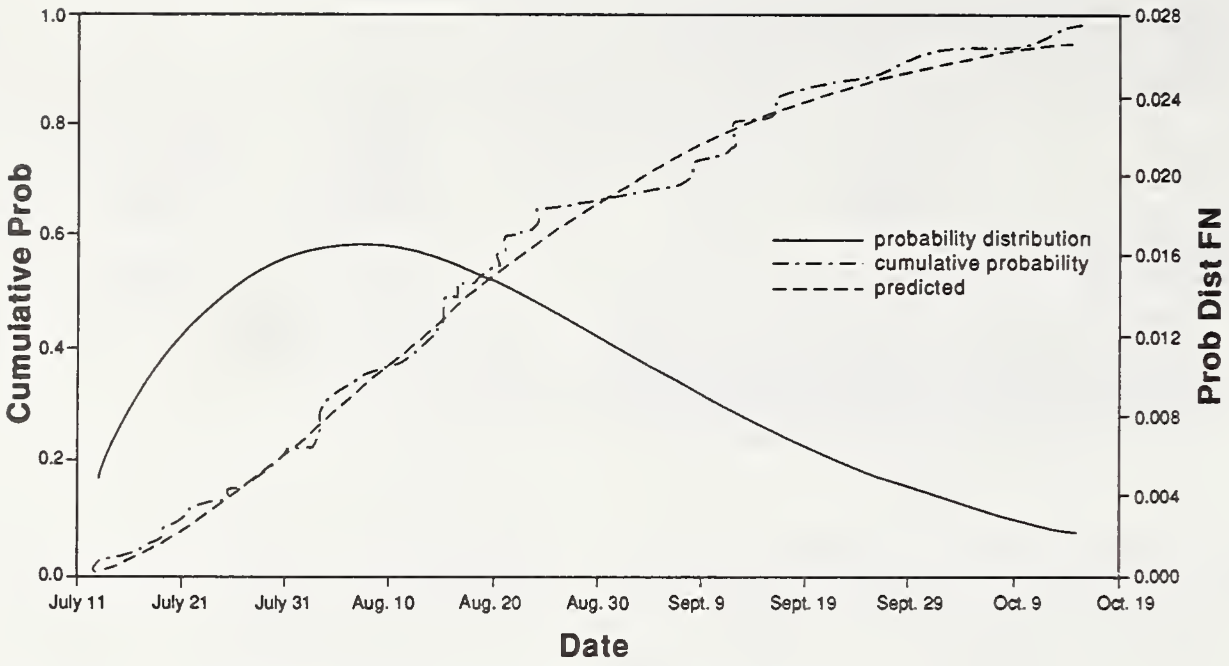

Figure 3—Cumulative probability and probability distribution for the first occurrence of a precipitation event producing 0.5 inches of precipitation in 5 days or less (data collected from 1970 to 1985 at the Gleason weather station on the Lewis and Clark National Forest in west-central Montana). The starting date was shifted 10 days from July 1 for the best least squares fit.

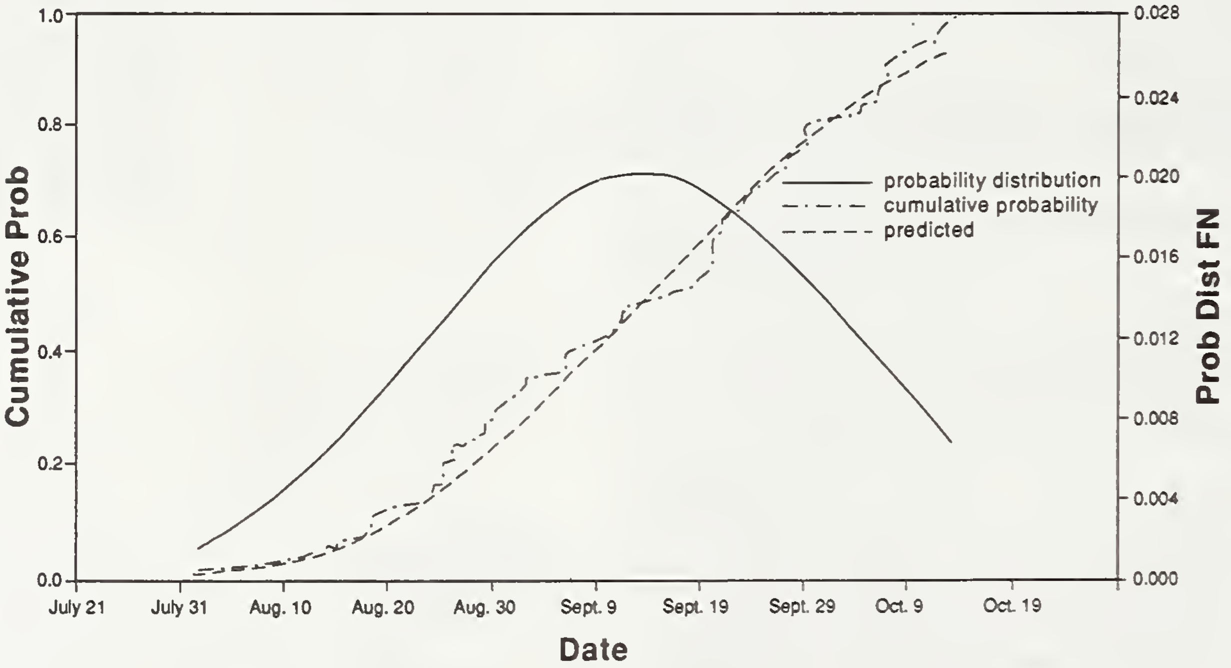

Figure 4—Cumulative probability and probability distribution for the first occurrence of a precipitation event producing 0.5 inches of precipitation in 5 days or less (data collected from 1972 to 1985 at the Redbox weather station on the Mt. Hood National Forest in central Oregon). The starting date was shifted 20 days from July 1 for the best least squares fit.

Table 2—Probability tables for the Lolo National Forest, Ninemile weather station. The "Prob" column gives the percent probability there will be a precipitation event on or before the corresponding date. A precipitation event is defined as 0.5 inches of precipitation within 5 days. For instance, the probability of a precipitation event by August 16 is 26 percent. The results are based on historical precipitation from 1970 to 1985

Date[1]	Prob	Date	Prob	Date	Prob	Date	Prob
July 1	0	Aug. 1	6	Sept. 1	52	Oct. 1	86
2	0	2	7	2	53	2	87
3	0	3	8	3	55	3	88
4	0	4	9	4	56	4	88
5	0	5	10	5	58	5	89
6	0	6	11	6	59	6	89
7	0	7	13	7	61	7	90
8	0	8	14	8	62	8	91
9	0	9	15	9	63	9	91
10	0	10	17	10	65	10	92
11	0	11	18	11	66	11	92
12	0	12	20	12	67	12	92
13	0	13	21	13	69	13	93
14	0	14	23	14	70	14	93
15	0	15	24	15	71	15	94
16	0	16	26	16	72		
17	0	17	27	17	73		
18	0	18	29	18	75		
19	0	19	30	19	76		
20	0	20	32	20	77		
21	0	21	34	21	78		
22	0	22	35	22	79		
23	0	23	37	23	80		
24	1	24	39	24	81		
25	1	25	40	25	81		
26	1	26	42	26	82		
27	2	27	44	27	83		
28	3	28	45	28	84		
29	3	29	47	29	85		
30	4	30	48	30	86		
31	5	31	50				

[1] To find the probability of a precipitation event between two specified dates, compute the difference between the two given probabilities: The probability of a precipitation event between August 7 and August 17 would be: P(Aug. 17) – P(Aug. 7) = 27 – 13 = 14 percent. The probability of a precipitation event between August 7 and September 9 would be: P(Sept. 9) – P(Aug. 7) = 63 – 13 = 50 percent.

7. Tabulate the results of calculations from the Weibull fit (for examples, see tables 2 to 5). Graphs such as those in figures 1 to 4 also may be prepared. The graphs show the cumulative probability of the first occurrence of 0.5 inch of precipitation in a 5-day time period and the probability distribution of the first occurrence of that event.

USE OF THE RESULTING DISTRIBUTION

An example of the probability calculation is shown here for the Lolo National Forest, Ninemile weather station (tables 1 and 2, fig. 1). The cumulative distribution is obtained from table 1 and equation (6), with

Table 3—Probability tables for the Bitterroot National Forest, Westfork weather station. The "Prob" column gives the percent probability there will be a precipitation event on or before the corresponding date. A precipitation event is defined as 0.5 inches of precipitation within 5 days. For instance, the probability of a precipitation event by August 16 is 32 percent. The results are based on historical precipitation from 1970 to 1985

Date[1]	Prob	Date	Prob	Date	Prob	Date	Prob
July 1	0	Aug. 1	11	Sept. 1	57	Oct. 1	88
2	0	2	12	2	59	2	89
3	0	3	13	3	60	3	90
4	0	4	15	4	62	4	90
5	0	5	16	5	63	5	91
6	0	6	17	6	64	6	91
7	0	7	19	7	66	7	92
8	0	8	20	8	67	8	92
9	0	9	22	9	68	9	93
10	0	10	23	10	69	10	93
11	0	11	25	11	71	11	93
12	0	12	26	12	72	12	94
13	0	13	28	13	73	13	94
14	0	14	29	14	74	14	94
15	0	15	31	15	75	15	95
16	0	16	32	16	76		
17	0	17	34	17	77		
18	0	18	36	18	78		
19	0	19	37	19	79		
20	1	20	39	20	80		
21	1	21	41	21	81		
22	2	22	42	22	82		
23	2	23	44	23	83		
24	3	24	45	24	84		
25	4	25	47	25	84		
26	5	26	48	26	85		
27	5	27	50	27	86		
28	6	28	52	28	86		
29	7	29	53	29	87		
30	8	30	55	30	88		
31	10	31	56				

[1] To find the probability of a precipitation event between two specified dates, compute the difference between the two given probabilities: The probability of a precipitation event between August 7 and August 17 would be: P(Aug. 17) – P(Aug. 7) = 34 – 19 = 15 percent. The probability of a precipitation event between August 7 and September 9 would be: P(Sept. 9) – P(Aug. 7) = 68 – 19 = 49 percent.

$\eta = 1.86709$ and $\sigma = 49.88164$. To find the chance of occurrence of the defined precipitation event on or before August 16, we use $w = 26$ (the number of days since July 21) and obtain:

$$P(\text{probability of a precipitation event by Aug. 16}) = 1 - \exp\left[-\left(\tfrac{26}{49.88}\right)^{1.87}\right] = 0.2564 \text{ or 26 percent.}$$

Tables 2, 3, 4, and 5 were filled out in just this way.

In order to calculate the probability that the precipitation event will occur between two dates, simply subtract the probabilities for the dates in question, as shown on tables 2 to 5. Note: On the Lolo National Forest (fig. 1), the highest probability of the first occurrence of precipitation shown by the probability distribution is near the end of August. This is a well-known rain event that coincides with the Missoula County Fair. It should also be noted from the cumulative probability (table 2 or fig. 1) that there is only about a 40 percent chance for a fire-stopping precipitation event by August 25. A 90 percent chance of such an event cannot be expected before October 7.

By contrast, the fire season is later at Mt. Hood National Forest in the Pacific Northwest. The best fit for the starting date is July 21. The probability distribution (fig. 4) shows the maximum probability for the first occurrence of the precipitation event to

Table 4—Probability tables for the Lewis and Clark National Forest, Gleason weather station. The "Prob" column gives the percent probability there will be a precipitation event on or before the corresponding date. A precipitation event is defined as 0.5 inches of precipitation within 5 days. For instance, the probability of a precipitation event by August 16 is 48 percent. The results are based on historical precipitation from 1970 to 1985

Date[1]	Prob	Date	Prob	Date	Prob	Date	Prob
July 1	0	Aug. 1	24	Sept. 1	69	Oct. 1	92
2	0	2	25	2	70	2	92
3	0	3	27	3	71	3	92
4	0	4	29	4	73	4	93
5	0	5	30	5	74	5	93
6	0	6	32	6	75	6	93
7	0	7	33	7	76	7	94
8	0	8	35	8	77	8	94
9	0	9	37	9	77	9	94
10	0	10	38	10	78	10	95
11	0	11	40	11	79	11	95
12	0	12	41	12	80	12	95
13	1	13	43	13	81	13	95
14	1	14	45	14	82	14	96
15	2	15	46	15	82	15	96
16	3	16	48	16	83		
17	3	17	49	17	84		
18	4	18	51	18	85		
19	5	19	52	19	85		
20	7	20	54	20	86		
21	8	21	55	21	87		
22	9	22	57	22	87		
23	10	23	58	23	88		
24	12	24	59	24	88		
25	13	25	61	25	89		
26	14	26	62	26	89		
27	16	27	63	27	90		
28	17	28	65	28	90		
29	19	29	66	29	91		
30	21	30	67	30	91		
31	22	31	68				

[1] To find the probability of a precipitation event between two specified dates, compute the difference between the two given probabilities: The probability of a precipitation event between August 7 and August 17 would be: P(Aug. 17) – P(Aug. 7) = 49 – 33 = 16 percent. The probability of a precipitation event between August 7 and September 9 would be: P(Sept. 9) – P(Aug. 7) = 77 – 33 = 44 percent.

be about September 15, with a 53 percent chance that fire-stopping precipitation will occur by then.

DISCUSSION AND CONCLUSIONS

We were pleasantly surprised by the fit of the Weibull distribution to the fire-stopping criterion. There should be little need to redo the coefficients of the distributions for some time, although they could be done each year. We expect that the process of generating this statistic can be automated if it should prove sufficiently useful. Two uses are immediately apparent:

1. Establishing criteria for deciding whether fires will be considered wildfires or prescribed natural fires, depending on the time of year they start, the drought conditions at the time, the area threatened, and the probability of fire-stopping precipitation.
2. Evaluating alternative suppression strategies and costs for ongoing fires that include a probability for a fire-stopping precipitation event.

We are certain that these suggestions do not exhaust the possible uses.

ACKNOWLEDGMENTS

We would like to take this opportunity to thank Joyce Schleiter who so capably carried out the statistical analysis in this paper.

Table 5—Probability tables for the Mt. Hood National Forest, Redbox weather station. The "Prob" column gives the percent probability there will be a precipitation event on or before the corresponding date. A precipitation event is defined as 0.5 inches of precipitation within 5 days. For instance, the probability of a precipitation event by August 16 is 7 percent. The results are based on historical precipitation from 1972 to 1985

Date[1]	Prob	Date	Prob	Date	Prob	Date	Prob
July 1	0	Aug. 1	0	Sept. 1	26	Oct. 1	81
2	0	2	1	2	28	2	82
3	0	3	1	3	30	3	84
4	0	4	1	4	32	4	85
5	0	5	1	5	33	5	86
6	0	6	1	6	35	6	87
7	0	7	2	7	37	7	88
8	0	8	2	8	39	8	89
9	0	9	2	9	41	9	90
10	0	10	3	10	43	10	91
11	0	11	3	11	45	11	92
12	0	12	4	12	47	12	93
13	0	13	4	13	49	13	93
14	0	14	5	14	51	14	94
15	0	15	6	15	53	15	95
16	0	16	7	16	55		
17	0	17	7	17	57		
18	0	18	8	18	59		
19	0	19	9	19	61		
20	0	20	10	20	63		
21	0	21	11	21	65		
22	0	22	12	22	66		
23	0	23	13	23	68		
24	0	24	15	24	70		
25	0	25	16	25	72		
26	0	26	17	26	73		
27	0	27	19	27	75		
28	0	28	20	28	77		
29	0	29	21	29	78		
30	0	30	23	30	80		
31	0	31	25				

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[1] To find the probability of a precipitation event between two specified dates, compute the difference between the two given probabilities: The probability of a precipitation event between August 7 and August 17 would be: P(Aug. 17) – P(Aug. 7) = 7 – 2 = 5 percent. The probability of a precipitation event between August 7 and September 9 would be: P(Sept. 9) – P(Aug. 7) = 41 – 2 = 39 percent.

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